In the News...

Spirit Rover finds dust devils on Mars

The Cosmic Distance Scale

Until the 1920's the scale of the Universe was not well defined:

- large Galaxy with everything inside it?

- small Galaxy with many other small galaxies around it

The Great Debate - Apr 26, 1920

Harlow Shapley & Heber Curtis debate "The Scale of the Universe" at the National Academy of Sciences.
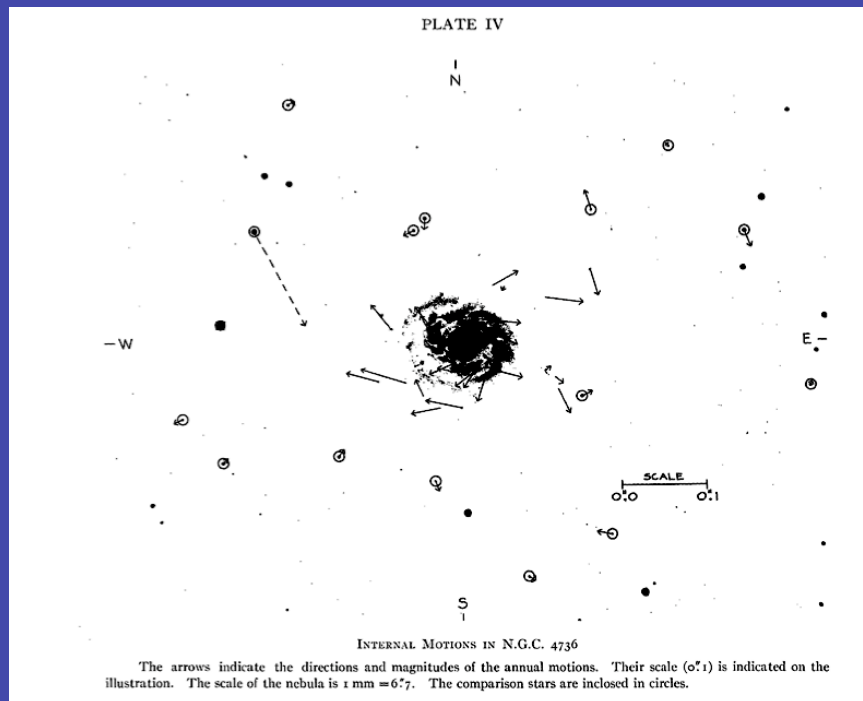
Curtis:
- Our galaxy is probably not more than 30,000 light-years in diameter, and perhaps 5,000 light-years in thickness
- The clusters, and all other types of celestial objects except the spirals, are component parts of our own galactic system.
- The spirals are a class apart, and not intra- galactic objects. As island universes, of the same order of size as our galaxy, they are distant from us 500,000 to 10,000,000, or more, light years.

Shapley:
- The galaxy is approximately 300,000 light- years in diameter, and 30,000 or more, light- years in thickness.
- The globular clusters are remote objects, but a part of our own galaxy. The most distant cluster is placed about 220,000 light-years away.
- The spirals are probably of nebulous constitution, and possibly not members of our own galaxy, driven away in some manner from the regions of greatest star density.

Van Maanen's Proper Motions

Photographic studies seemed to suggest rotation in the "spiral nebulae" (M101, M33, NGC 4736)

PLATE IV

INTERNAL MOTIONS IN N.G.C. 4736

The arrows indicate the directions and magnitudes of the annual motions. Their scale (0".1) is indicated on the illustration. The scale of the nebula is 1 mm = 6".7. The comparison stars are inclosed in circles.

Van Maanen, 1922, CMWO, 243, p208

subsequently shown to be incorrect

Hubble Identifies Cepheids in M31

Edwin Hubble, using the 100-in Hooker telescope on Mount Wilson telescope, resolved outer parts of M31 and M33 into stars

Hubble showed from photographic photometry that 12 were Cepheid variables (from the lightcurve shape)

(assumptions: Cepheids were with the spirals; absorption unimportant; Cepheid P-L relation universal)

Derived D=285 kpc for M31, M33 (modern distance: 784 kpc - Hubble used wrong P-L)

M31,M33 well beyond the bounds of the Milky Way

Astronomy 191 Space Astrophysics
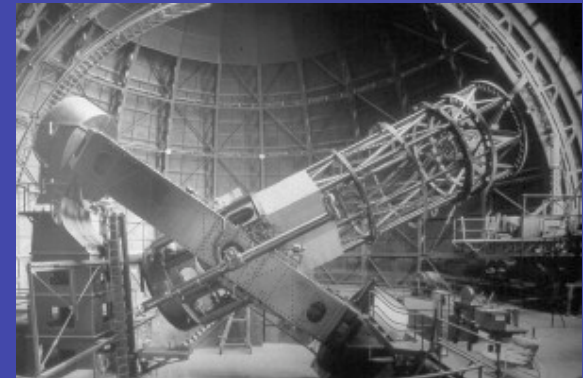
Cosmic Distance Scale

V.M. Slipher (1917): radial velocities of spiral nebulae are +570 km/s on average (velocity of M31 -300 km/s)

Milton Humason finds redshift of +40,000 km/s for Bootes Cluster

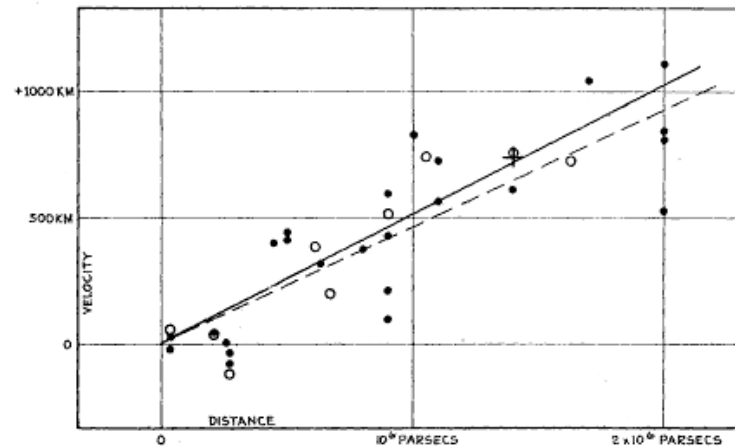Hubble (1929) showed that the distances and velocities to extragalactic nebula were related linearly:

FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.

Astronomy 151 Space Astrophysics

The Hubble Law

The Hubble law is

$$v = H_o r$$

where H_o is the Hubble constant = 71 km s^{-1} Mpc^{-1}

Velocities are determined by measuring the redshifts of spectral lines in galaxies & AGN:

$$\frac{\lambda}{\lambda_0} = \sqrt{\frac{1+\beta}{1-\beta}} = 1+z$$

where λ is the observed wavelength and λ_0 the rest wavelength

$$\beta = v/c$$

$$z = v/c \text{ for } v<<c$$

$$r = v/H_0$$

$$H_0 = 71^{+4}_{-3} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

from WMAP

Clusters of Galaxies

Galaxies come in:

- groups (Local Group contains the Milky Way, M31, LMC, SMC...)

- clusters (Local Group part of the Virgo Cluster)

- superclusters (Virgo Cluster part of the Virgo-Coma supercluster)

Why Study Clusters?

Clusters of Galaxies form the largest and most massive "collapsed" objects in the Universe

the inter-cluster medium maintains a record of chemical evolution in the member galaxies ("closed boxes")

They are useful probes of the structure of the Universe on large scales

They define the density perturbations in the early Universe

They help define the amount of missing matter

Cluster identification

Clustering of "nebulae" was noted by Charles Messier in his studies of nebulous objects in the sky in the mid-late 1700's

George Abell, Fritz Zwicky and others recognized physical clustering of galaxies in spatial and redshift distributions
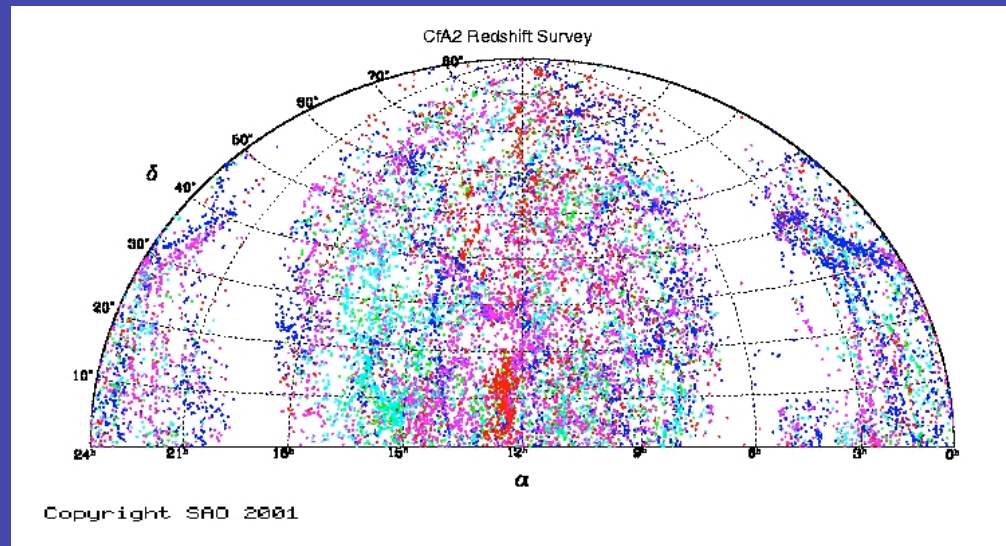
Galaxy cluster map from the CfA redshift survey

J. Huchra and M. Geller 1998

The Virgo Cluster
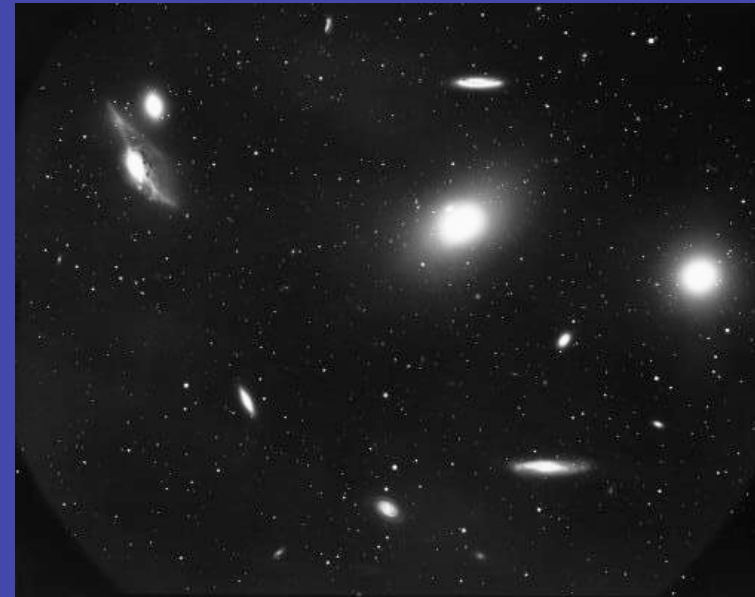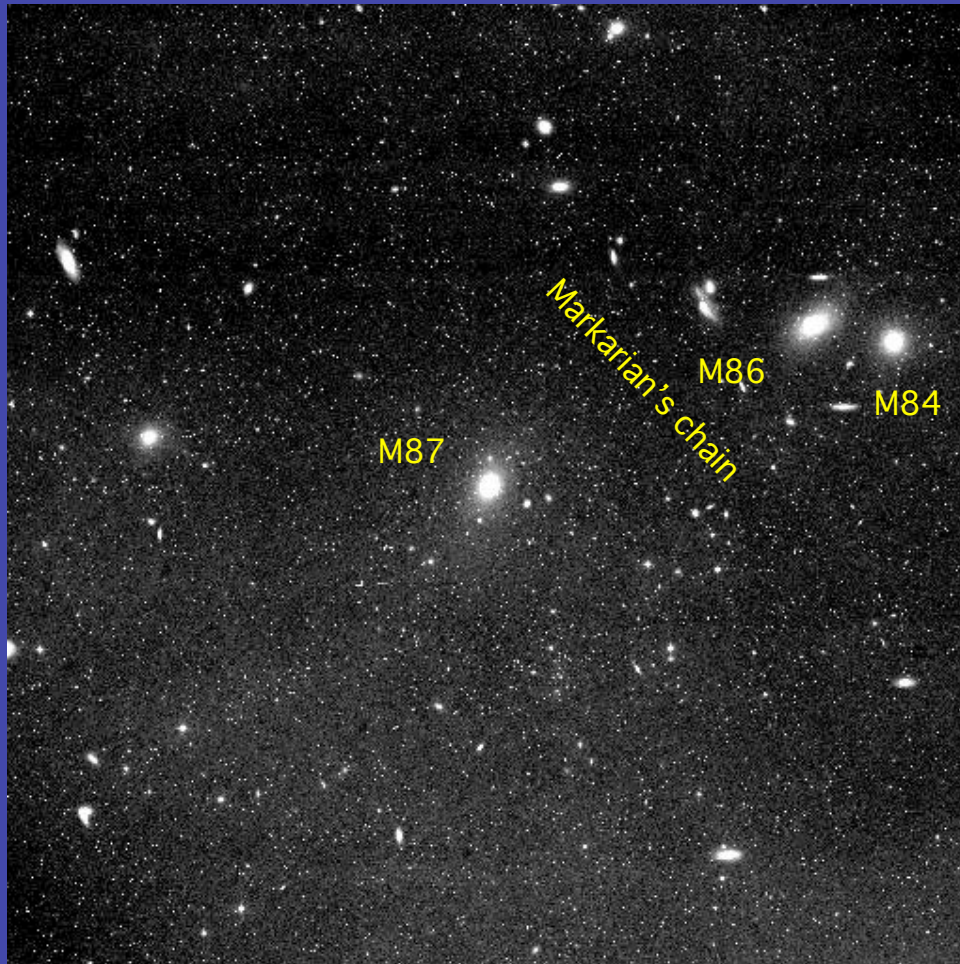
- The Virgo Cluster is the closest cluster to us (18 Mpc).
- Contains about 2000 galaxies
- Virgo receding from us at about 1,100 km/sec
- Eventually Local Group will fall into Virgo
- IC 3258: V=-517 km/s

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The Coma Cluster

- Prototype of rich cluster (many 1000's of galaxies)
- Mostly Ellipticals
- about 100 Mpc
- Diameter ~ 1Mpc

Credit & Copyright: O. Lopez-Cruz (INAOEP) et al., AURA, NOAO, NSF

The Hercules Cluster

credit: Jim Misti

- Young cluster
- Deficit of ellipticals
- Lots of interactions
- Similar to young clusters in the early universe?

Nearby Clusters
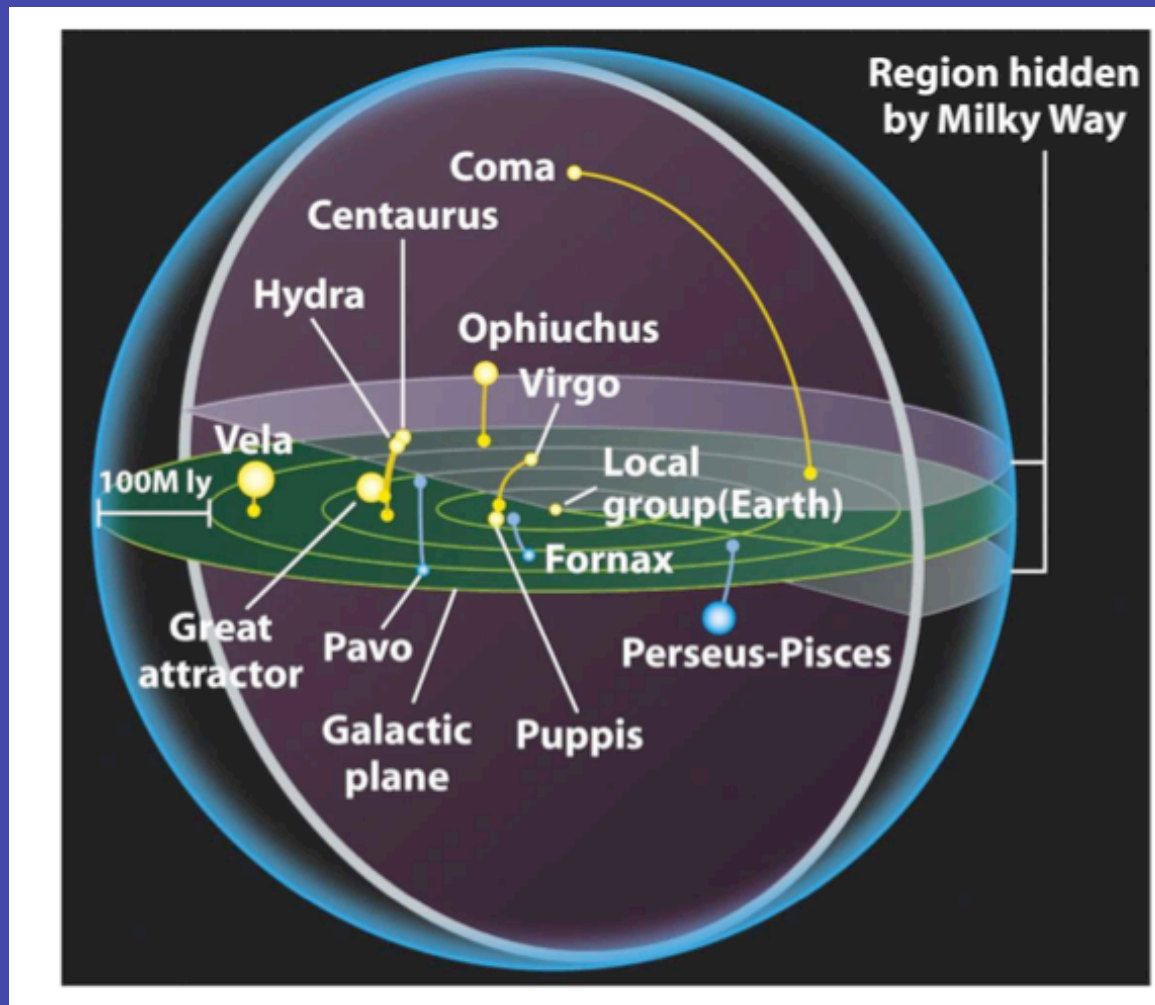
Optical properties of Clusters

Cluster galaxies can interact

Interactions tend to turn spirals into ellipticals

Generally clusters dominated by a giant elliptical galaxy usually containing a supermassive black hole

The Intracluster Medium

The ICM exists between the member clusters

ICM origins:

- primordial matter

- stripped ISM from galaxies

- material ejected from stellar winds, SNe, jets, etc...

Dynamics of Galaxies in Clusters

The "relaxation time" is the approximate time between encounters between galaxies and is given by

$$t_{relax} = \frac{(rv)^3}{3G^2 mM \ln(rv^2/Gm)}$$

For a typical cluster, t_{relax} ~ few Myrs < age of universe

A galaxy in a typical cluster will have undergone many interactions so that the cluster is in dynamical equilibrium (galaxy velocity distribution follows a Maxwellian distribution, or, is "virialized")

Cluster Masses

If a cluster is virialized, then the virial theorem can be used to estimate the cluster mass:

Virial Theorem: Total kinetic energy =

-1/2 Gravitational potential energy

or

$$M_{cluster} \simeq \frac{2Rv^2}{G}$$

for Coma, $R \simeq 1\text{Mpc}$, $v \simeq 1000\text{km s}^{-1}$ so $M_{coma} \simeq 5 \times 10^{14} \text{ M}_\odot$

ICM Heating Processes

What Heats the ICM?

- compression during cluster formation

- supersonic shocks from accretion

- other contributions: SNe, AGNs...

Typical temperatures should be 10^7-10^8 K

Cooling times expected to be longer than the age of the Universe

Clusters should be strong, observable X-ray sources

Advantages of X-ray Observations

X-ray observations of clusters are very useful:

- can be used to find clusters (extended, hot emission not associated with any galactic object)

- X-ray emission reveals the properties of the (hidden) ICM

- Most of the baryons are in the X-ray emitting gas

- X-ray properties (temperature, line strengths) are tightly correlated to cluster properties (mass, composition)

- X-ray Universe is rather sparse, so clusters have high contrast

- X-ray emission depends on density squared, so emission is more concentrated than the optical distribution of cluster galaxies

X-ray Studies of Clusters

Early (1960's) X-ray experiments indicated some clusters were X-ray sources

Einstein provided the first real X-ray images of clusters
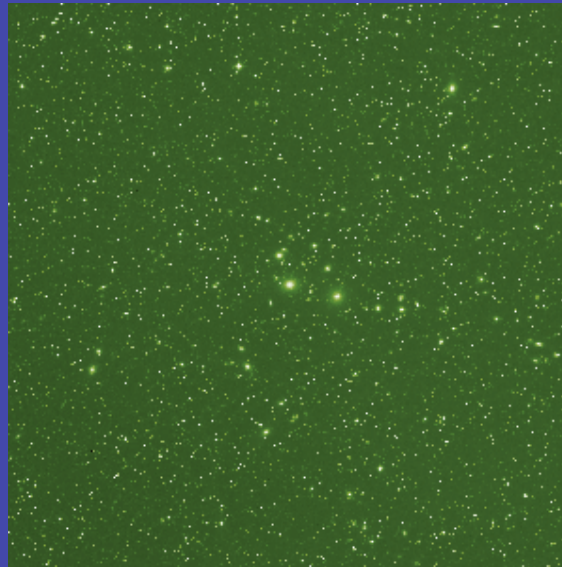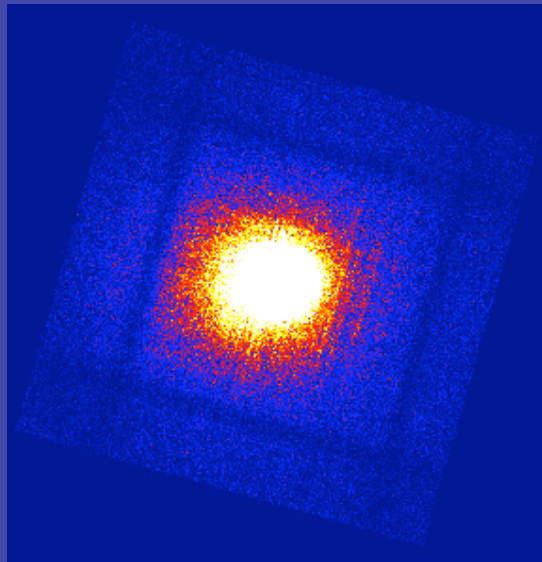
Perseus cluster: left X-ray (Einstein); right optical

X-ray Properties

X-ray emission bright, extended

Usually not centered on a single galaxy

In some clusters X-ray emission shows substructure

In virialized clusters X-ray emission is smooth

X-ray Brightness Profiles
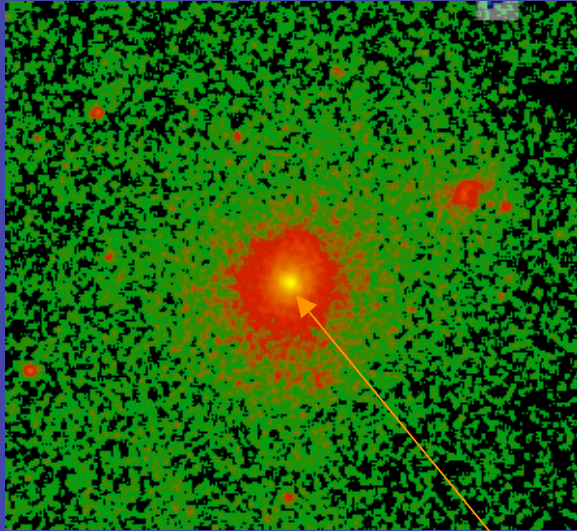
Virgo Cluster

X-ray brightnesses strongly peaked due to ρ^2 dependence of the emission

X-ray brightness profile has extended "wings"
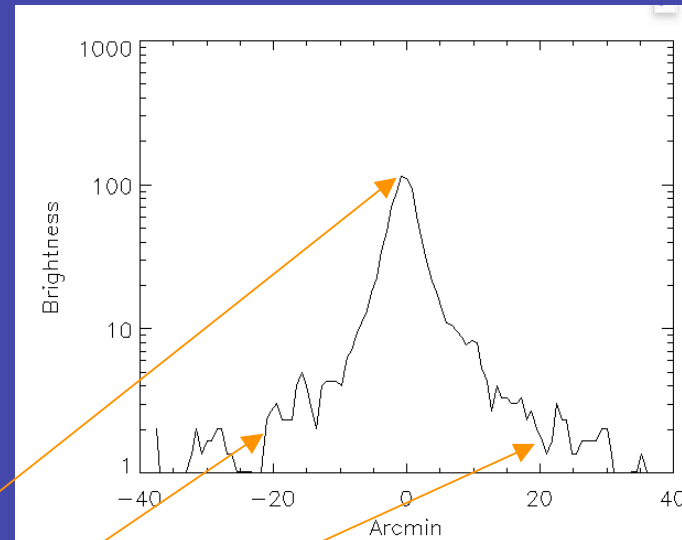
$$S \propto \left[1 + (r/a)^2\right]^{-3\beta+1/2}; \beta = \frac{\mu m_H \sigma_v^2}{3kT}$$

King Profile

X-ray Data Analysis

Extract spectra in radial sections around the peak of the emission

Fit each spectrum with an appropriate model (thermal bremsstrahlung, for ex) which gives X-ray flux and temperature as a function of R

observed flux in an energy band $E_0 - E_1$ for a given temperature

$$f = \int_{E_0}^{E_1} \epsilon(E, T) dE \boxed{\int \rho_e \rho_i dV}$$

for thermal bremsstrahlung,

emission measure

$$\epsilon(E, T) \sim T^{1/2} e^{-E/kT}$$

Use flux to get $\rho_e \rho_i$ (for assumed volume) as a function of r, then solve for M(<r)

Cluster Mass Profiles

For an ideal gas in hydrostatic equilibrium,

$$\frac{dp}{dR} = -\frac{GM(<R)\rho_{gas}(R)}{R^2}$$

$$p = \rho_{gas}k_BT/\mu m_p$$

$$M(<R) = -\frac{k_BTR}{G\mu m_p}\left(\frac{d\log\rho_{gas}}{d\log R} + \frac{d\log T}{d\log R}\right)$$

From X-ray spectra can measure both the gas density and the temperature profiles
From the temperature and the redshift, can derive the cluster mass
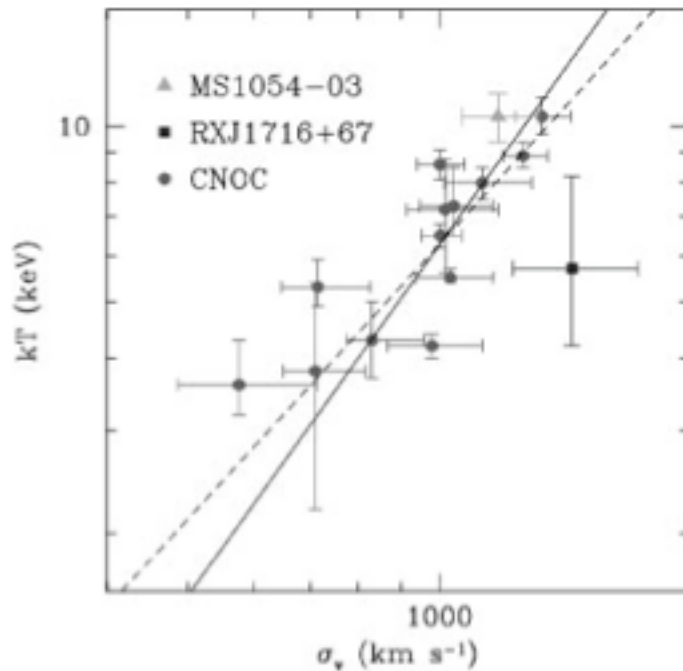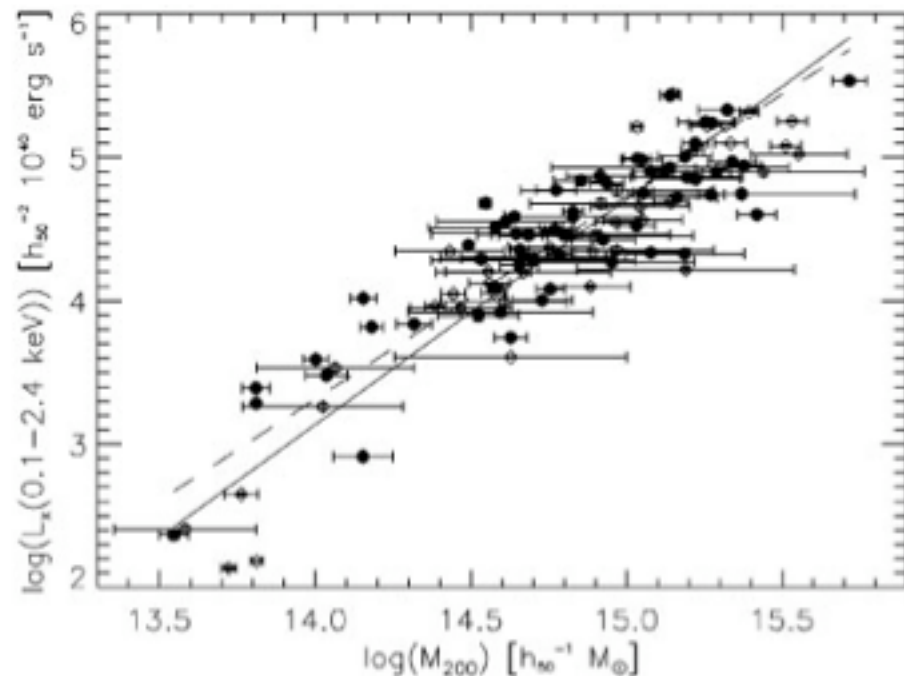
X-ray Analysis: A2589

Buote & Lewis 2004

$$\rho \propto r^{-1}(r_s + r)^{-2}$$
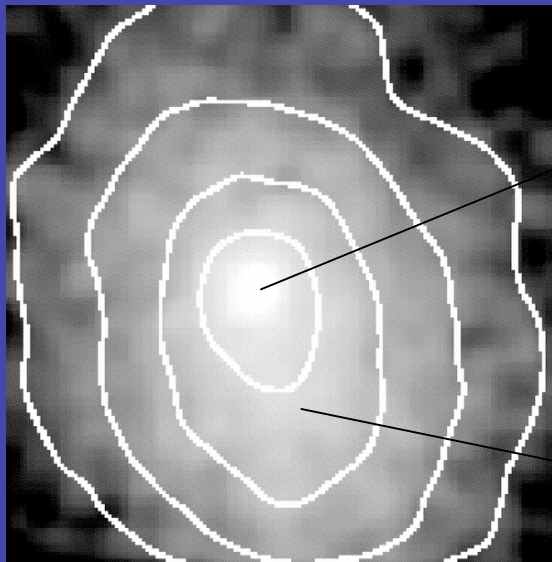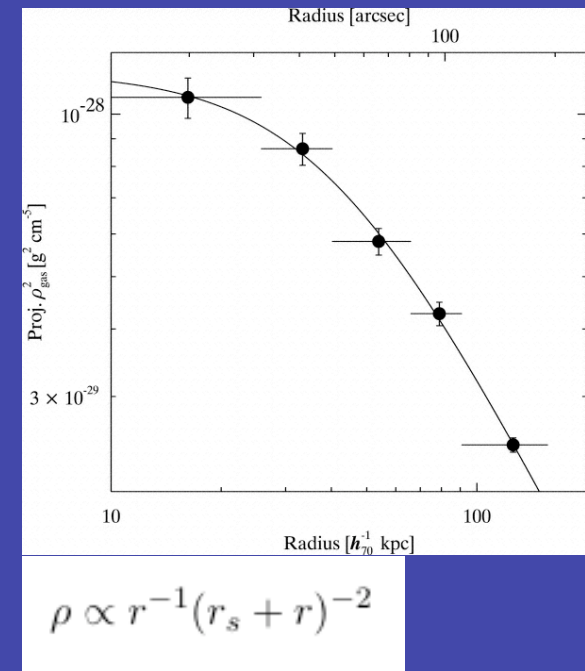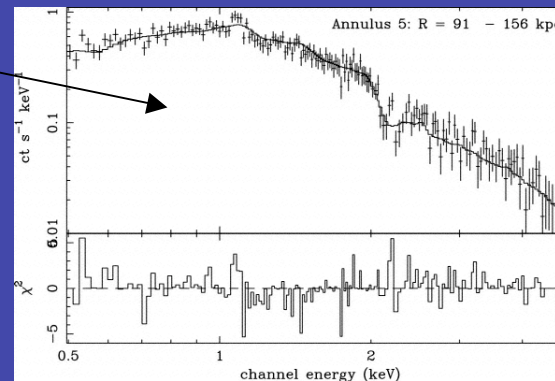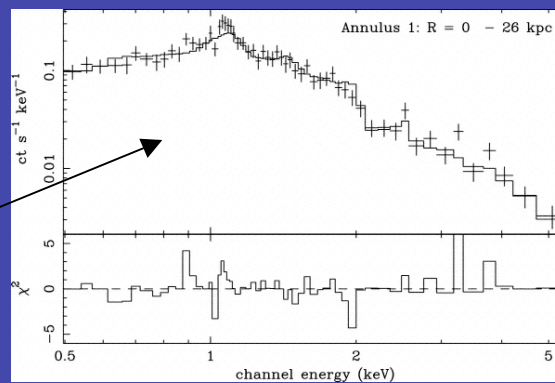
X-ray Calibrations

X-ray temperatures correlated with cluster dispersion velocity (i.e. cluster mass)

X-ray luminosity well correlated with cluster mass; Lx $\propto M^{1.8}$

ICM Cooling

Cooling can be important in the densest part of the ICM. For thermal bremsstrahlung cooling
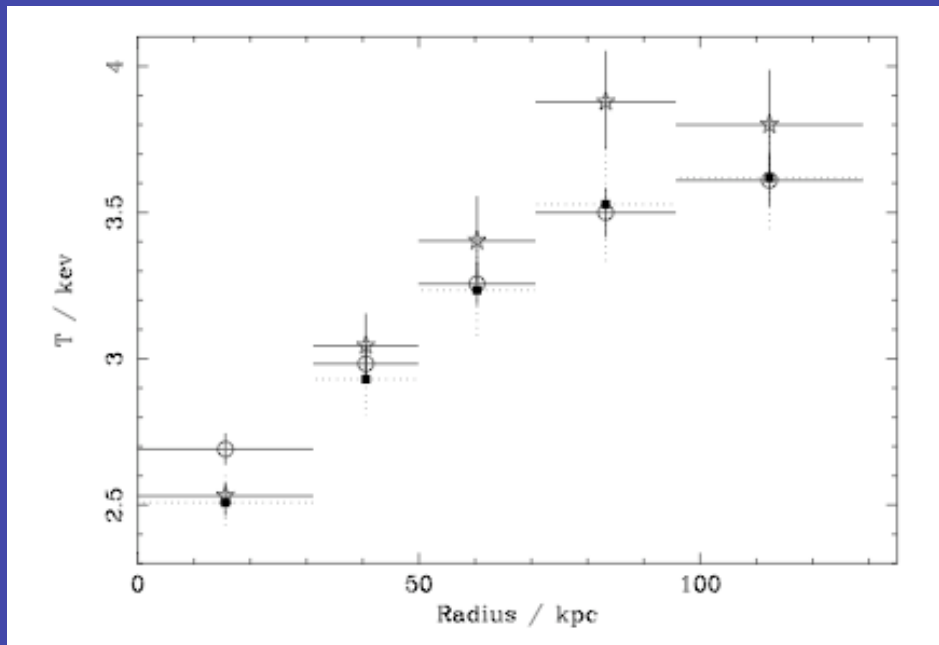
$$t_{cool} \simeq 8.5 \times 10^{10} \ \mathrm{yr} (n/10^{-3} \ \mathrm{cm}^{-3})^{-1} (T/10^8 \ \mathrm{K})^{1/2}$$

if $n > 7 \times 10^{-3}$ then $t_{cool} < t_{universe}$

Temperature Profiles

X-ray brightness profiles strongly peaked due to radiative cooling

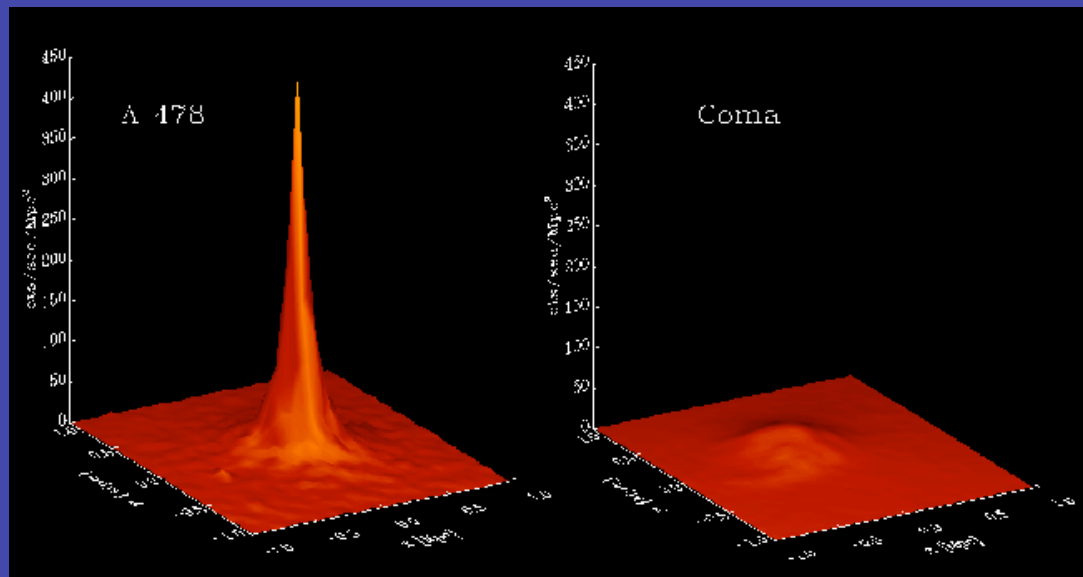X-ray temperature profiles show minima near the peaks

XMM-Newton & Chandra temperature profiles of Abell 2597
(Morris & Fabian 2005)

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Cooling Flows

Cool gas in the center of cluster provides less pressure support to the outer gas

Gas should fall into the cluster center: Cooling Flow

Comparison of cooling flow cluster (A478) and a non-cooling flow cluster (Coma).

http://www-xray.ast.cam.ac.uk/oday/clusters_cflows.html

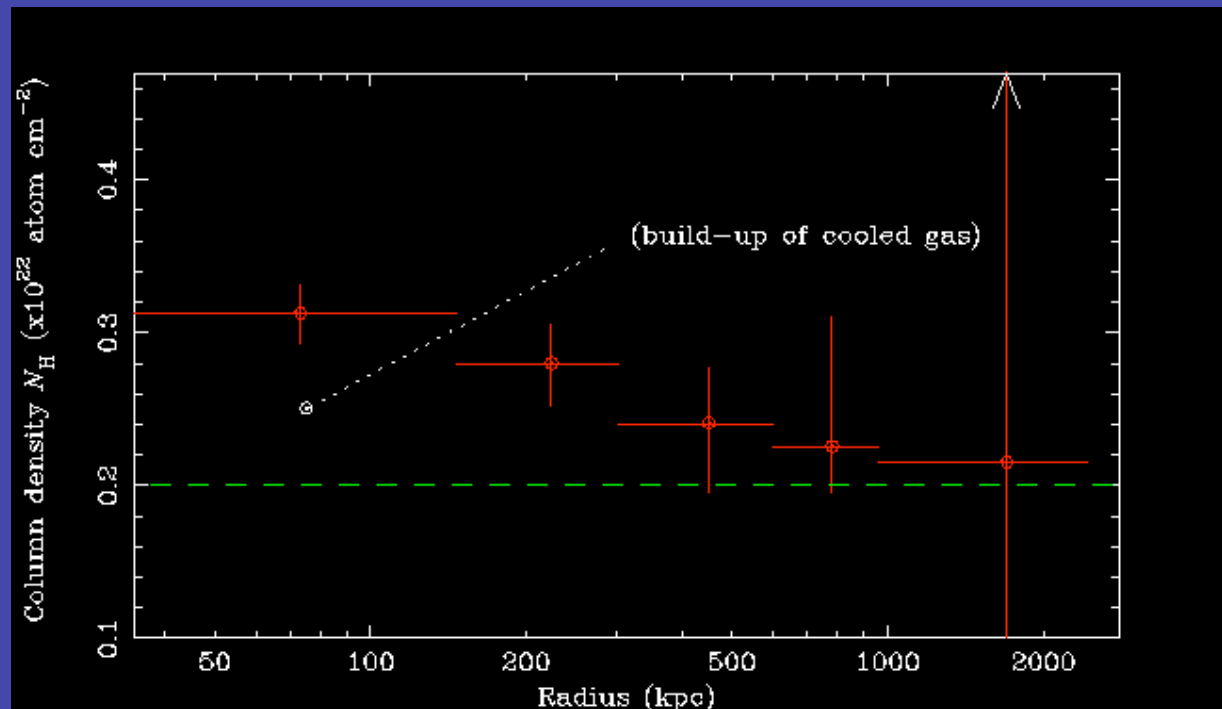# Cooling Flow Simulation

NASA/CXC/M.Weiss

Effects of Cooling Flows

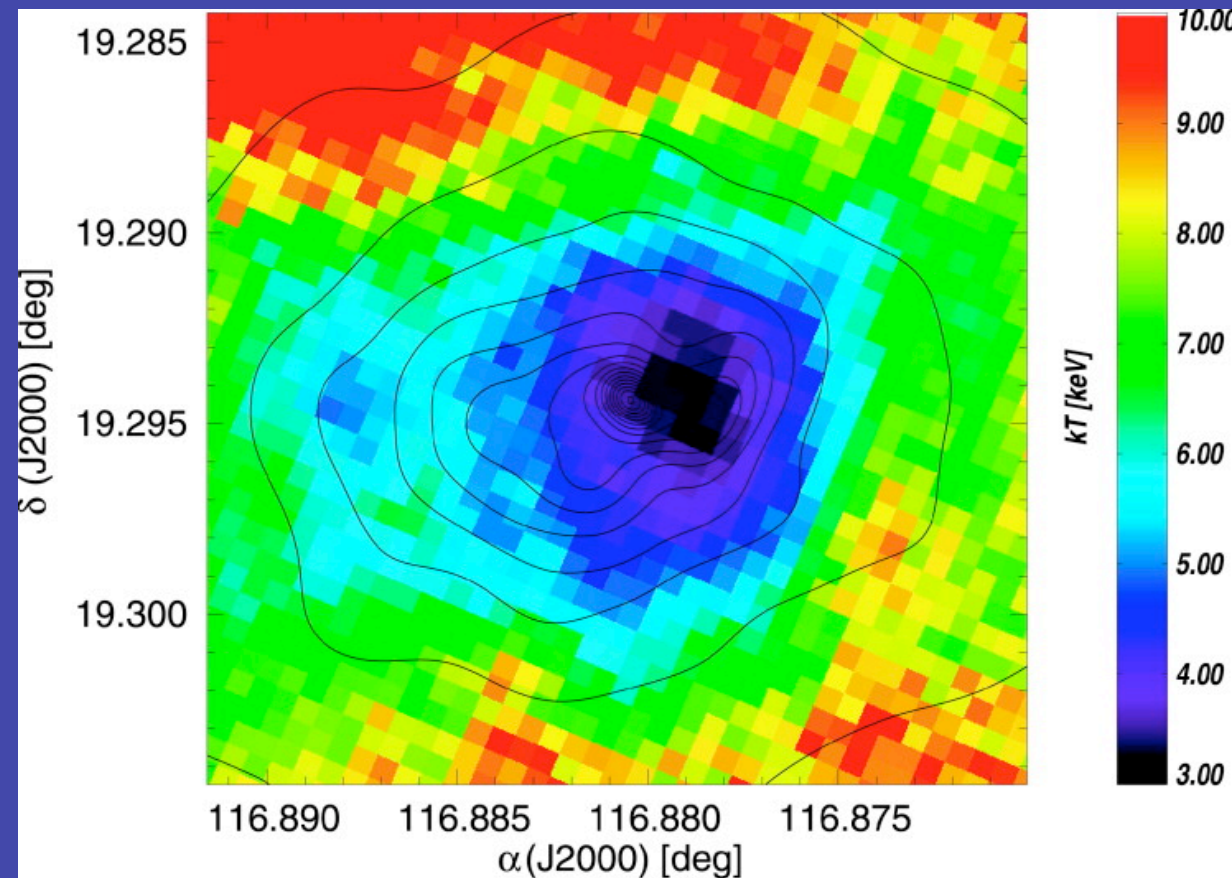As material cools in the center of the cluster, it forms dense blobs

Densest blobs cool fastest; eventually lose all their thermal energy

Builds up a reservoir of cold dense molecular clouds

Star formation?

Temperature Maps

Temperature map of PKS0745-191 showing apparent offset between peak X-ray brightness (contours) and minimum X-ray temperature (colorscale)
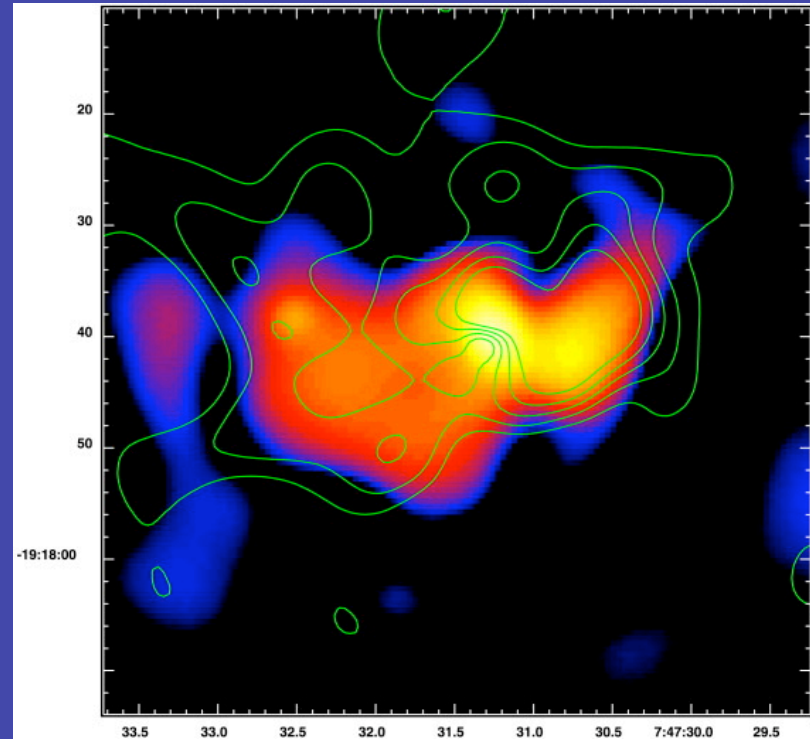
Hicks et al. 2002

Substructure

Center of clusters sometimes show asymmetries: substructure

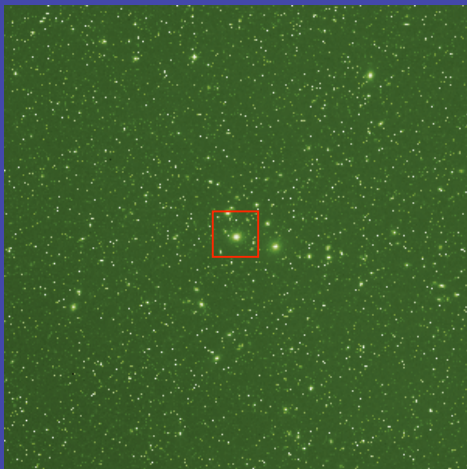Substructure caused by
- mergers?
- galactic interactions?

PKS 0745-191 substructure from Chandra observation (Hicks et al. 2002)
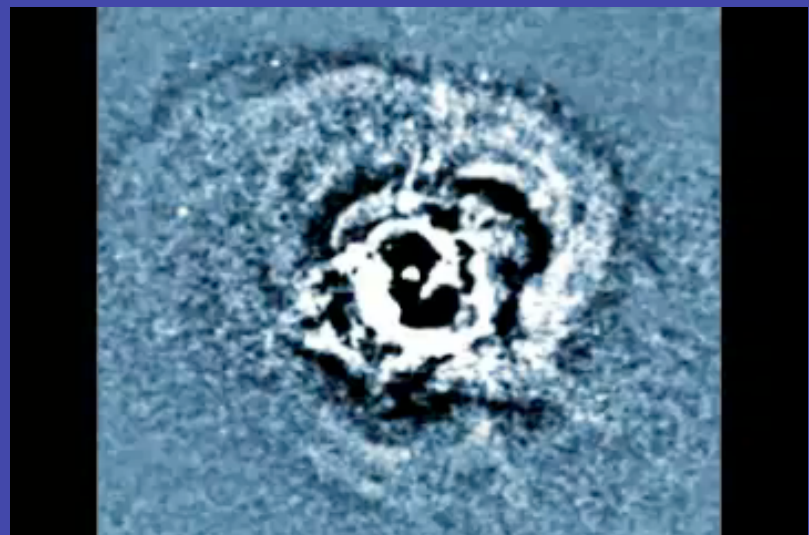
AGN in Clusters

The presence of AGN in clusters can have a significant effect on the ICM in terms of changing the density and temperature profiles near the AGN
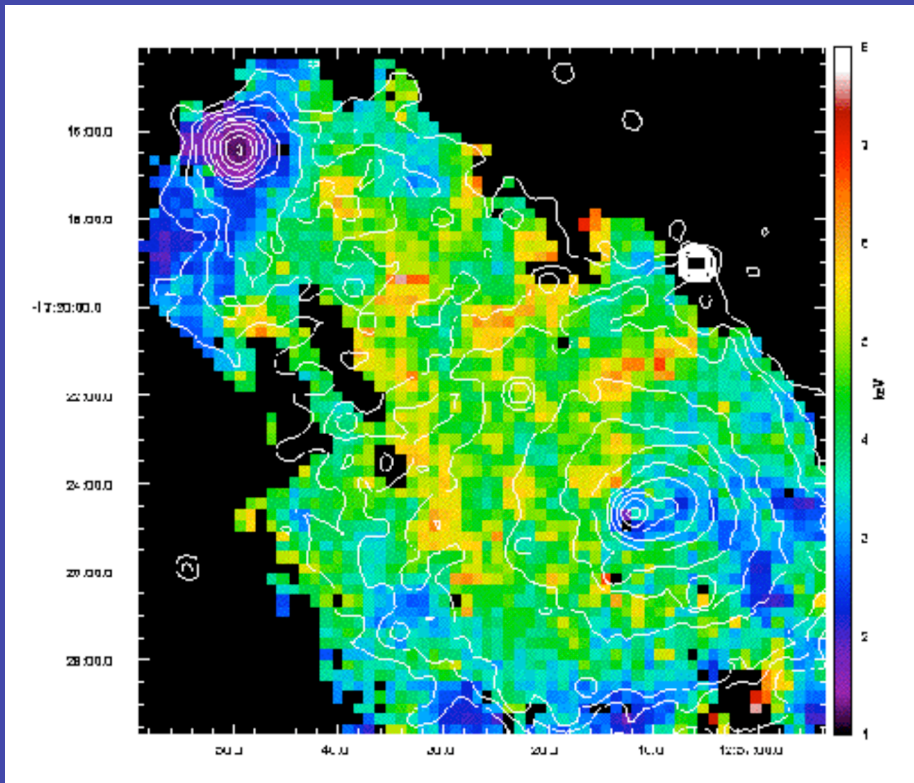
Ex: Perseus Cluster

Central galaxy is NGC 1275, a Seyfert with a supermassive black hole
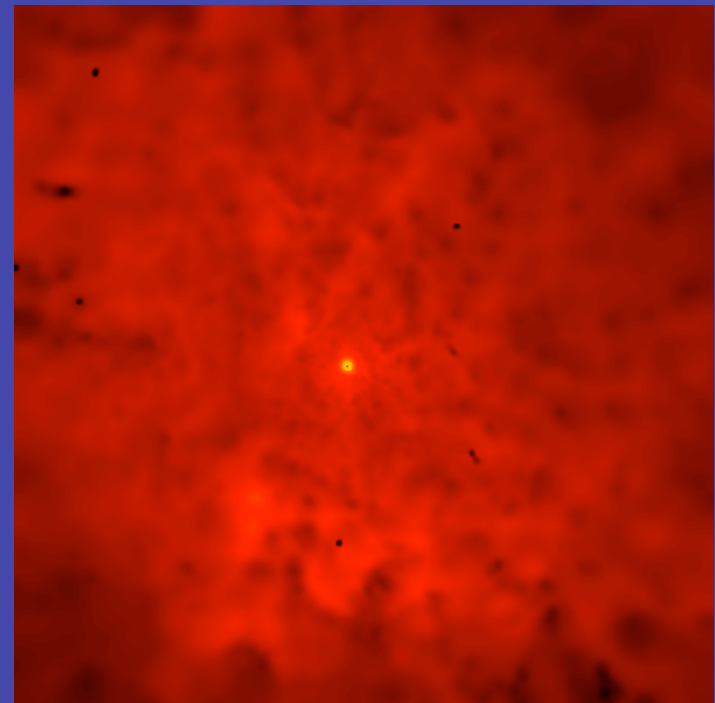
Perseus Simulation

Activity in the black hole in NGC 1275 (due to swallowing another galaxy?) produces strong jets which make huge cavities in the ICM. Mechanical heating may be re-heating cooling flow.

Cluster Mergers

Abell 1644: XMM shows 2 separate peaks: evidence of merger of small cluster with larger one?

Dark Matter

Smith (1936) & Zwicky (1937) note that the mass implied by the dynamics of the member galaxies in Virgo exceeded the visible mass by a good factor if the cluster were gravitationally bound: $M/L \sim 100$

First evidence of Dark Matter

Largest clusters have about 5x more matter in hot gas than in visible stars

X-ray studies and gravitational lensing masses for clusters imply that the baryonic matter (stars, hot gas) makes up only 10% of the mass that we see.

Nature of the dark matter Unknown...
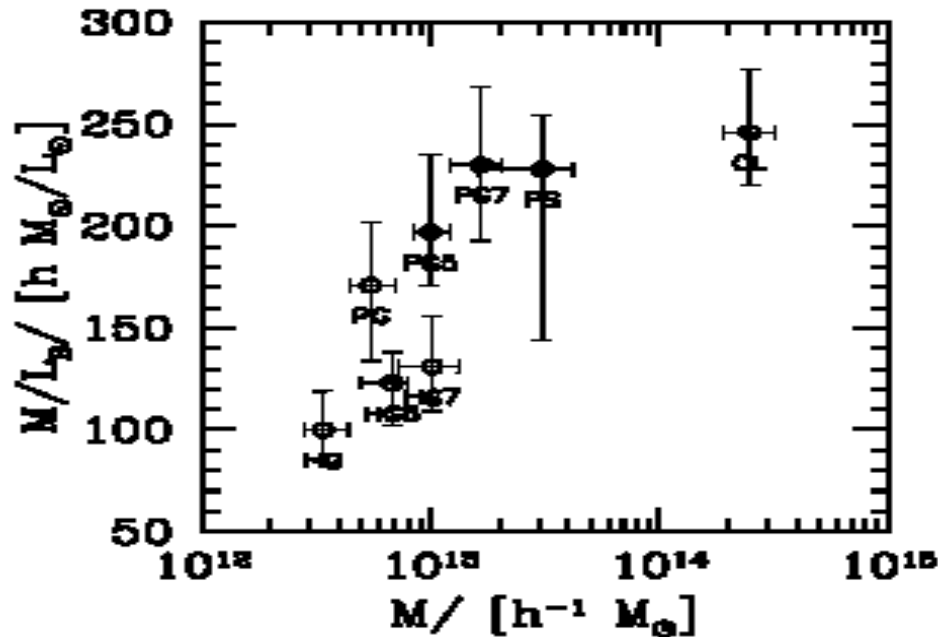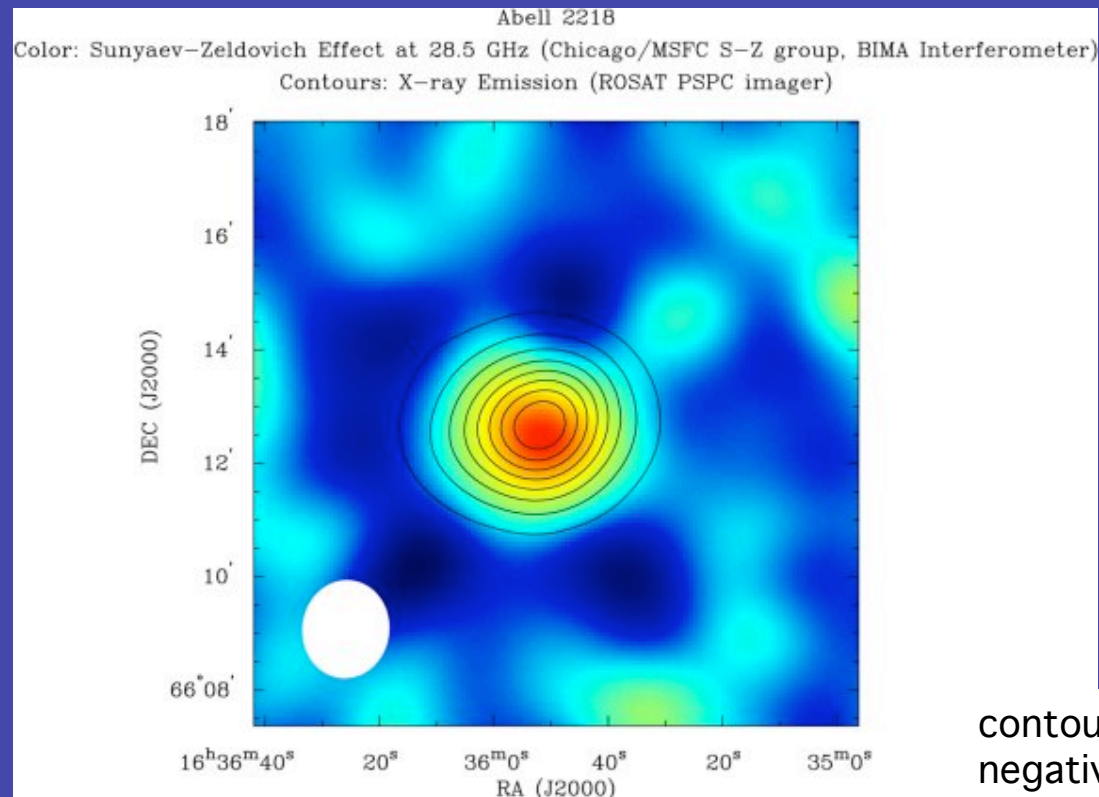
M/L ratios

FIG. 8.—Behavior of mass-to-light ratio vs. cluster mass for the sample of clusters (CL), poor systems (PS), and percolation and hierarchical NOG groups of different richness (PG and HG, respectively). Circles are median values with 90% c.l. error bars.

- M/L ratios typically > 100

- more massive clusters tend to have more dark matter

- Assuming M/L ~ 5 for stars (at least in the Milky Way) the total amount of mass in stars is ~ 5/120 ~ 4%

- About 17% of the mass is in the baryons in the hot gas

- The rest - 79% - is in dark matter

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Finding Clusters: Sunyaev-Zel'dovich Effect

Hot electrons in ICM should inverse compton scatter cosmic microwave background photons from the Big Bang

CMB should look fainter near clusters due to scattering of microwave photons to other energies

Abell 2218
Color: Sunyaev–Zeldovich Effect at 28.5 GHz (Chicago/MSFC S–Z group, BIMA Interferometer)
Contours: X–ray Emission (ROSAT PSPC imager)
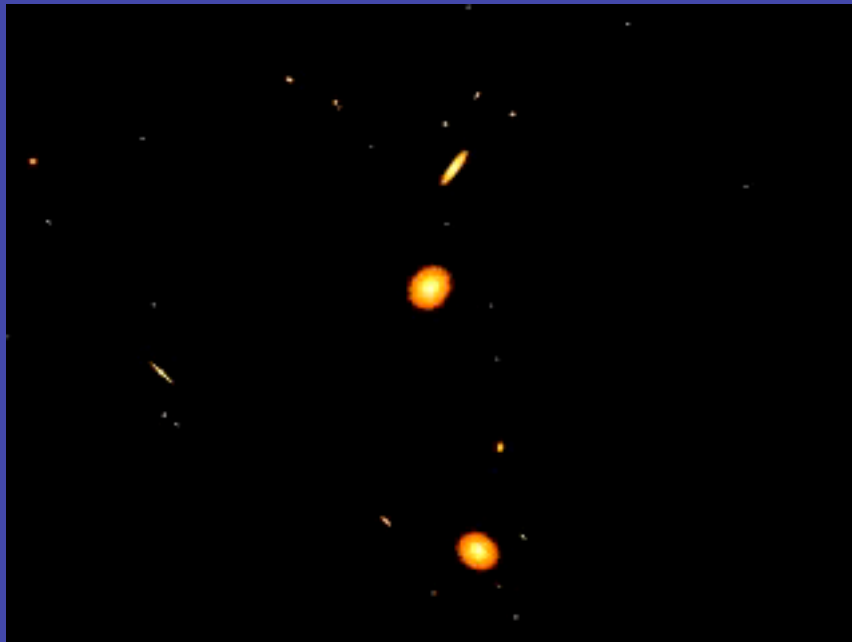
contours are negative intensity

Gravitational Lensing

Clusters distort spacetime and bend light paths (gravitational lensing)
Distribution of lensed sources can provide information on mass and mass distribution of the cluster
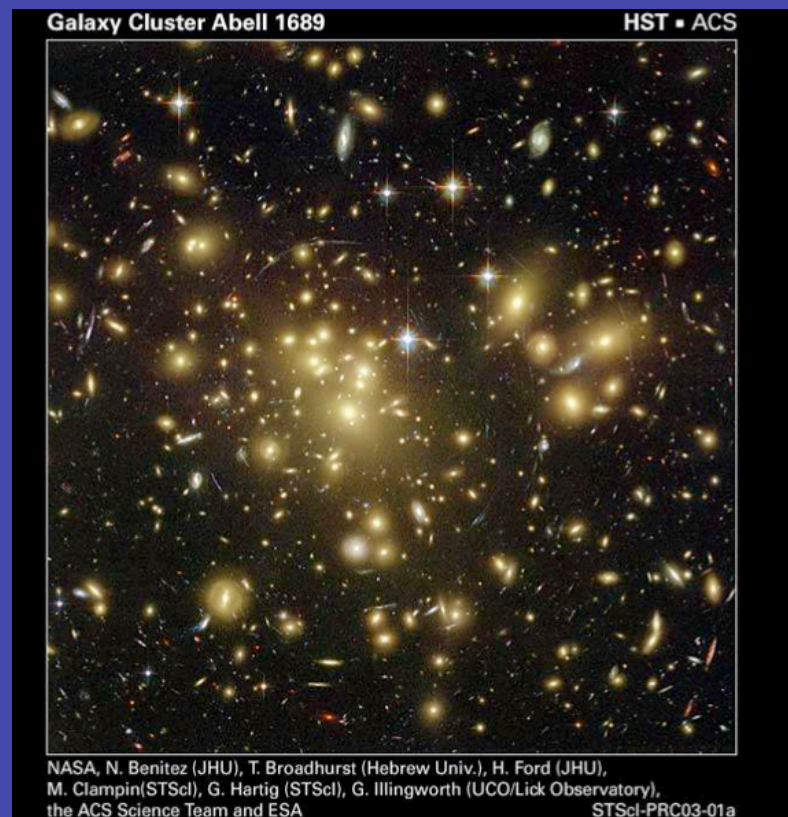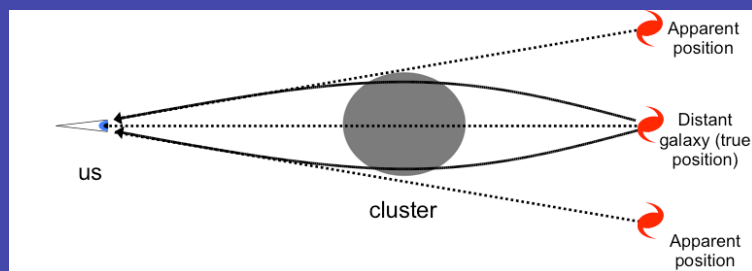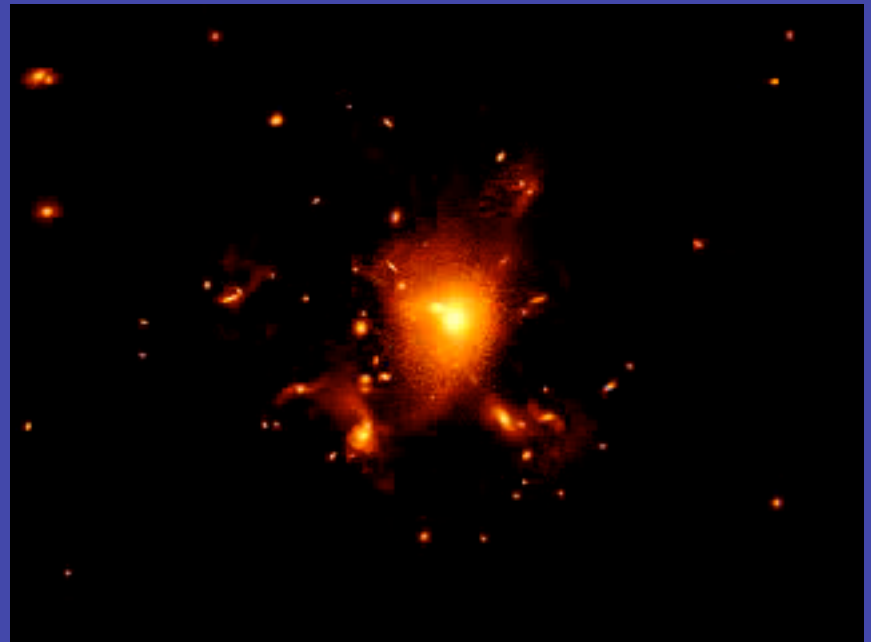
Cluster Formation & Evolution

The evolution of the cluster over 10 billion years
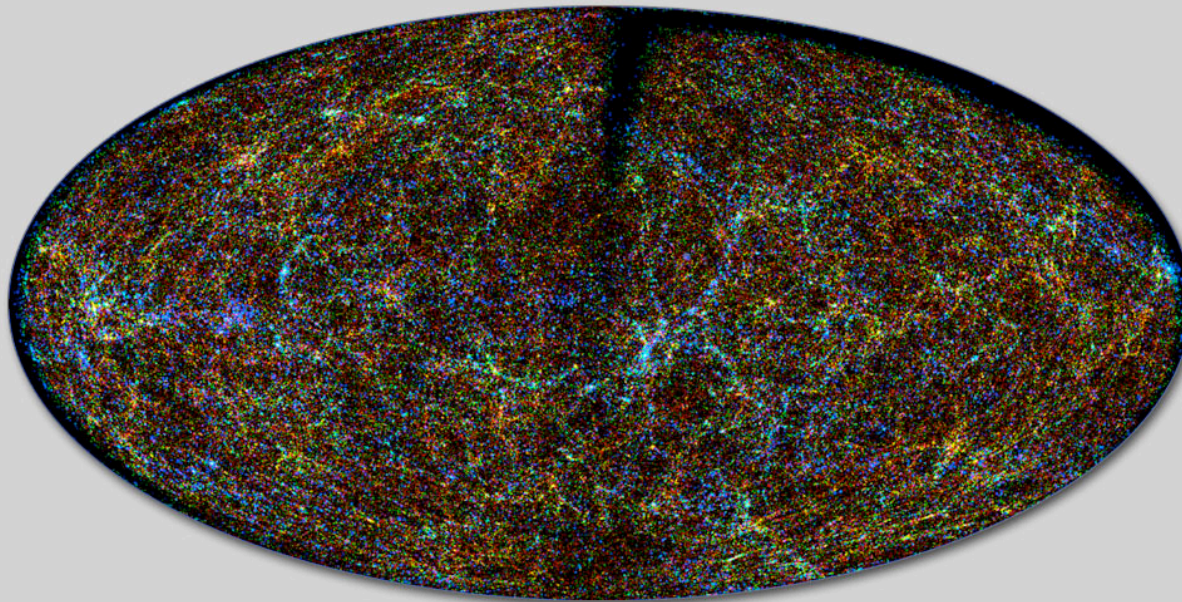
The cluster at z=0.35

John Dubinski
http://www.cita.utoronto.ca/~dubinski/nbody/
http://www.cita.utoronto.ca/~dubinski/bigcluster.html

Large Scale Structure

blue: near

red: far

2MASS*howcase*

Galaxies of the Infrared Sky Near and far structures in the local universe are color-coded by galaxy brightness

Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

- Universe is composed of a web of superclusters

- Understanding where and when these superclusters formed directly determines the scale of the density bumps in the early universe

Summary

Galaxies form groups, clusters, superclusters

In a cluster most of the mass (baryonic and non-baryonic, or "dark") is in the intra cluster medium

X-rays are a good way to study the ICM since it's very hot

Cooling flows can form at the center of the ICM, producing dense molecular clouds (and stars?)